



## The 8 September 2017 Tsunami Triggered by the $M_w$ 8.2 Intraplate Earthquake, Chiapas, Mexico

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**Abstract**—The 8 September 2017,  $M_w$  8.2 earthquake offshore Chiapas, Mexico, is the largest earthquake in recorded history in Chiapas since 1902. It caused damage in the states of Oaxaca, Chiapas and Tabasco, including more than 100 fatalities, over 1.5 million people were affected, and 41,000 homes were damaged in the state of Chiapas alone. This earthquake, an intraplate event on a normal fault on the oceanic subducting plate, generated a tsunami recorded at several tide gauge stations in Mexico and on the Pacific Ocean. Here, we report the physical effects of the tsunami on the Chiapas coast and analyze the societal implications of this tsunami on the basis of our post-tsunami field survey. The associated tsunami waves were recorded first at Huatulco tide gauge station at 5:04 (GMT) 12 min after the earthquake. We covered ground observations along 41 km of the coast of Chiapas, encompassing the sites with the highest projected wave heights based on our preliminary tsunami model (maximum tsunami amplitudes between 94.5° and 93.0°W). Runup and inundation distances were measured along eight sites. The tsunami occurred at low tide. The maximum runup was  $\sim 3$  m at Boca del Cielo, and maximum inundation distance was 190 m in Puerto Arista, corresponding to the coast in front of the epicenter and in the central sector of the Gulf of Tehuantepec. Tsunami scour and erosion was evident along the Chiapas coast. Tsunami deposits, mainly sand, reached up to 32 cm thickness thinning landward up to 172 m distance.

**Key words:** Post-tsunami survey,  $M_w$  8.2 intraplate earthquake, Mexican subduction, runup, tsunami early warning.

### 1. Introduction

The 8 September 2017,  $M_w$  8.2 earthquake offshore Chiapas, Mexico (Fig. 1), was the largest earthquake in the recorded history of Chiapas since 1902. Few historical tsunamis have been recorded near the coast of Chiapas, but only one event caused by a magnitude  $M_s$  7.7 on 22 March 1928 in Puerto Angel Oaxaca, having caused no reported fatalities (Nuñez-Cornu and Ponce 1989; Sanchez and Ferreras 1993; NGDC/WDS 2017). The 8 September 2017,  $M_w$  8.2 earthquake caused damage in the states of Oaxaca, Chiapas and Tabasco; the official estimates exceed 100 fatalities, more than 1.5 million people affected, and 41,000 homes damaged in the state of Chiapas alone. Although the epicenter of this earthquake was close to the Mexican subduction zone where the Cocos plate subducts under the North American plate, this was not an interplate event, a megathrust earthquake, but rather a deep intraplate event within the subducting oceanic plate, near the slab bend from a shallow to steeper dip at greater depth in the slab (e.g., Hayes et al. 2012; Okuwaki and Yagi 2017; Hjorleifsdottir et al. 2017), with a focal mechanism indicating normal faulting (strike 311, dip 84.4, and rake 94.7, the plane given is the preferred plane) at 58 km depth (SSN 2017). The 8 September 2017 earthquake generated a tsunami that was recorded at several tide gauge stations in Mexico and around the Pacific Ocean (SMN 2017; PTWC 2017). Here, we report the physical effects of the tsunami (runup) on the Chiapas coast and analyze the societal implications of this tsunami on the basis of our field observations.

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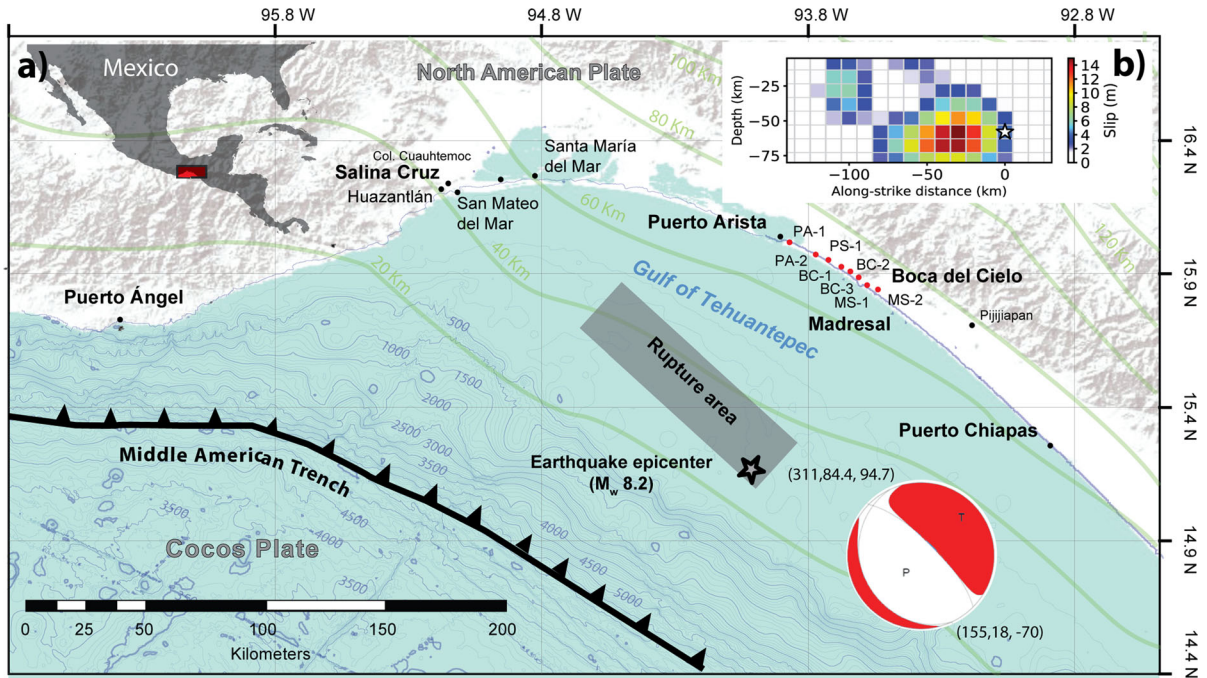


Figure 1

Map shows subducting Cocos plate along the Middle American trench, and North America upper plate; star—8 September 2017 earthquake epicenter; gray-shaded rectangle—rupture area; beach ball—moment tensor indicating a steep normal fault. Inset a: study area; b: source inversion model; red dots—post-tsunami study sites: *PA1* and *PA2* Puerto Arista 1 and 2, *PS1* Playa del Sol, *BC1*, 2 and 3 Boca del Cielo 1, 2 and 3, *MS1* and *MS2* Madre Sal 1 and 2. Green lines—slab depth contours (Hayes et al. 2012)

### 1.1. The 8 September 2017 Chiapas Earthquake

The 8 September 2017  $M_w$  8.2 earthquake occurred at 04:49:21 GMT (23:49:21 local time), and was located at 14.85°N and 94.11°W, at 58 km depth, at the oceanic slab bending (SSN 2017). More than 4326 aftershocks (until 23 September) were registered, of which the largest reached  $M_w$  6.1 (SSN 2017). The maximum slip in the  $M_w$  8.2 earthquake from a slip inversion of the tide gauge data is 15 m (Fig. 1). Also, preliminary coseismic offsets associated with this earthquake determined from interferometry data suggest subsidence of the coast near Salina Cruz and uplift up to 20 cm in the surveyed area (NASA/JPL Caltech Advanced Rapid Imaging and Analysis Team 2017).

## 2. Methodology

### 2.1. Tsunami Model

For the finite fault inversion geometry, we use the automatic hypocenter location from SSN (14.85°N,

94.11°W, 58 km). We then use the nodal planes from the regional W-phase moment tensor inversion also carried out automatically by SSN. The nodal planes are one sub-vertical and one sub-horizontal plane with strike, dip, and rake as 310°/81°/−98° and 169°/12°/−51°. We discretize each plane into 25 × 10 square-shaped subfaults of 10 × 10 km dimensions. We attempted inversion on each of the nodal planes and ultimately found a much better solution using the sub-vertical fault plane.

The tide gauge and DART buoy data are de-tided by simple bandpass filtering. The high-pass corner has a period of 2 h and the low-pass corner has a period of 5 min. Inversion is then carried out using a linear code (Melgar and Bock 2015). The inverse problem is rank deficient and is regularized by penalizing the model norm, i.e., we require the model with the smallest possible amount of slip to match the data. We assume a homogeneous half space with a 45 GPa shear modulus and, because tsunami data are not sensitive to rupture speed, we perform a static inversion.

Green's functions for each subfault to tsunami gauge pair are computed using the procedure described in Melgar and Bock (2013), which we summarize here. For each subfault, the analytical solutions of Okada (1985) are used to estimate seafloor deformation due to 1 m of slip on each subfault. This seafloor deformation is then the input into a tsunami propagation model (Berger et al. 2011) and tsunami output is collected at the location of the four tide gauges and one DART buoy [Deep-ocean Assessment and Reporting of Tsunamis—DART from NOAA (<http://www.ndbc.noaa.gov/dart/dart.shtml>)]. These tsunami time series are considered the GFs that map slip to tsunami perturbations.

The model in figure S1 is the result of the inversion and the fits to the tide gauges are shown in figure S1. As discussed in Melgar and Bock (2013), we only attempt to fit the first wavelength at each wave gauge, fitting later arrivals is not advisable. Under the linear assumption, later arrivals will not be well modeled because there are complex interactions with the coast and shallow bathymetry. The fits are good, and overall variance reduction is high (75%) for three of the tide gauges and the DART buoy (Figure S1). The tide gauge at Puerto Chiapas has a poor fit, likely because the first arrival is not direct but rather a reflection from the coastline. In any case, removing it from the inversion does not change the overall model. In a forthcoming work, we will discuss a joint inversion with more regional geophysical data to better constrain and explain the source process. For the purposes of this paper, a simple source model suffices.

With the slip inversion from Fig. 1 we use the Okada (1985) analytical solutions to calculate the vertical deformation of the seafloor on a  $500 \times 500$  km grid surrounding the source. This deformation is once again the initial condition for a non-linear tsunami simulation. We collect simulation output at 1 km intervals along the coastline immediately opposite the source. The maximum predicted amplitudes are shown in Fig. 2. This entire modeling process was carried out within 48 h of the earthquake and is what was used to guide the tsunami survey.

The preliminary tsunami model used a source inversion, coastal tide gauge data and one DART south of Acapulco, 43413 station, data; it suggested

that the maximum amplitudes of the tsunami were between  $-94.5$  and  $-93.0$  W (Fig. 2). Following this tsunami model, we selected sites for measurements.

## 2.2. Field Survey

Five days after the earthquake, a post-tsunami survey team was deployed to the coast of Chiapas on 12–16 September 2017. The main objective of this survey was to observe the physical effects of the tsunami. The team surveyed coastal villages between Las Marias and El Madresal (Figs. 1, 2), encompassing the sites with the highest projected wave heights based on the preliminary tsunami model (Fig. 2). The survey team covered ground observations along 41 km of the coast of Chiapas inside the Gulf of Tehuantepec. During the survey, we documented tsunami runup and inundation distances, and tsunami-induced erosion and deposition. Also, local eyewitnesses were interviewed following the IOC protocols (ITST 2014).

Runup and inundation distances were measured with an RTK GPS and using a Sokkia B40 level along eight sites. We corrected runup data with predicted astronomical tidal levels at the time of the tsunami (SMN 2017).

We used two drones (Quantum and F550 models) to document tsunami inundation and tsunami physical effects on the coast morphology in areas with limited access. We developed digital elevations models and photo-mosaics with 2 cm resolution, and DEMs were georeferenced using GPS field-collected data.

## 3. Results

### 3.1. Tide Gauge Data

Tide gauge data indicate 11.3 cm of coastal coseismic subsidence at Salina Cruz (SC), and Puerto Chiapas (PCh) does not show significant deformation (Figure S2). Some coastal areas show uplift; however as better data is coming out, we observe that the eastern side of the Gulf of Tehuantepec shows subsidence and the western part shows uplift. The plots in Figure S2 show that the filtered tide gauge

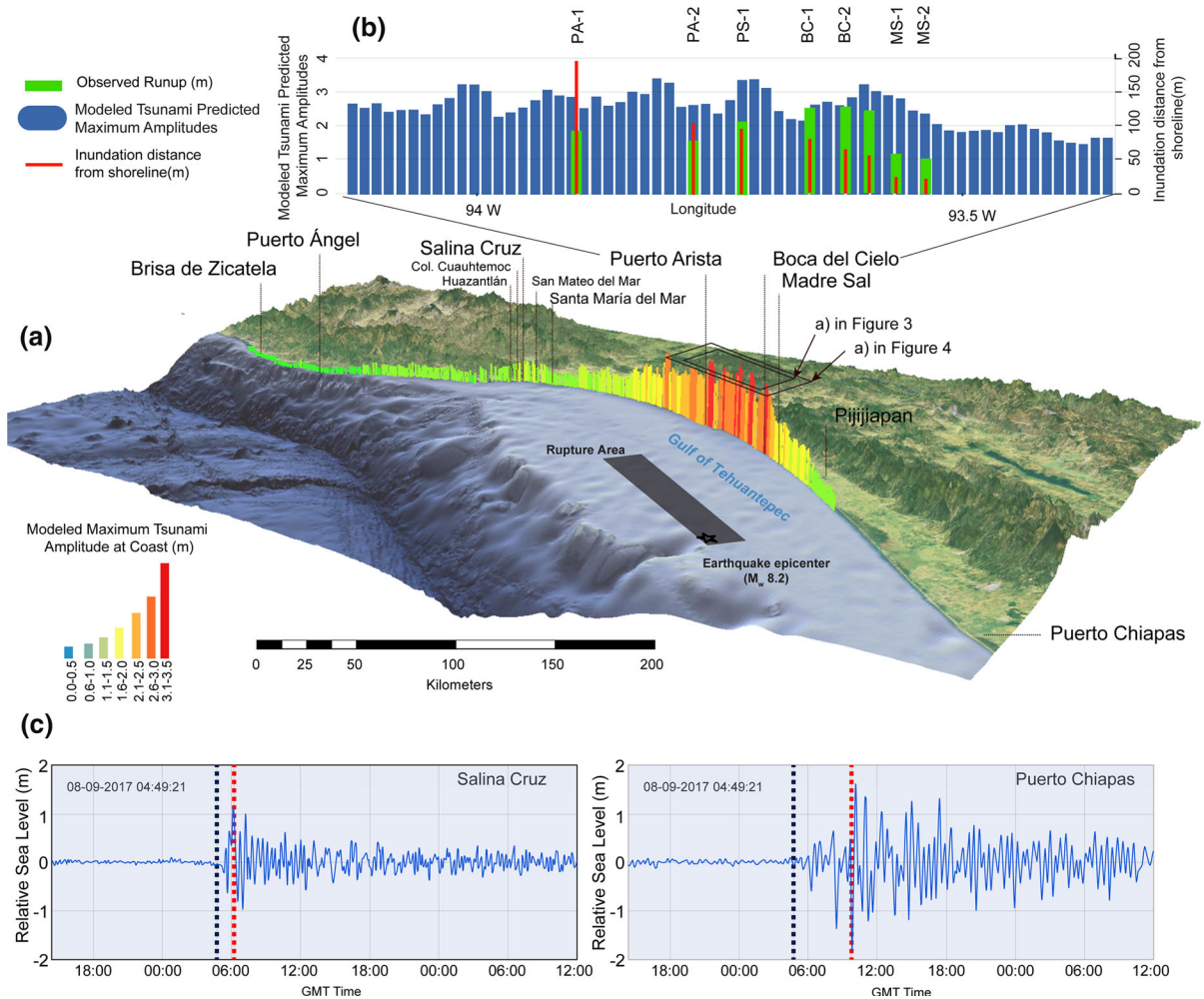


Figure 2

8 September 2017 observed tsunami runup, inundation distance, and modeled maximum amplitude at Chiapas coast. **a** 3D-bathymetry of the subducting Cocos plate and the North America plate along the trench; colored columns show maximum modeled tsunami amplitudes at coast; **b** surveyed sites show observed runup (green), inundation distances (red) and maximum modeled tsunami amplitudes at coast (blue); **c** tide gauge data at Salina Cruz and Puerto Chiapas stations (tidal signal removed); time of earthquake—dashed black line; time of maximum amplitude at stations—dashed red line

data indicate a positive increment (deeper water) on water level associated with subsidence. Note that two of the tide gauges are on the hanging wall of the normal fault so they should experience subsidence, while two of the tide gauges are on the foot wall and should experience uplift; this is exactly what we observe in Figure S2.

The associated tsunami wave propagated radially away from the source and was recorded first at Salina Cruz tide gauge station at 05:13 (GMT) and at 05:25 (GMT) at Puerto Chiapas (Fig. 2).

Tide gauge data from several stations along the Mexican Pacific coast, such as Puerto Angel, Huatulco, Acapulco, Zihuatanejo, Lazaro Cardenas and Manzanillo, registered the maximum tsunami height as below 1 m and in most cases less than 0.5 m (SMN 2017; PTWC 2017). The 8 September 2017 tsunami was registered around the Pacific as far as the Galapagos Islands, Easter Islands, Marquesas, Hawaii, Tahiti, and Pago-American Samoa, and by at least two of the DARTS in the Pacific (PTWC 2017).

### 3.2. Runup and Inundation

Tide level at SC and PCh before the arrival of the first tsunami wave was low 0.37 m below sea level at 5:14:2 (GMT) and 0.42 m at 5:27 (GMT), respectively, on 8 September 2017. It is noteworthy mentioning that low tide was present ( $-0.39$  m average of SC and PCh stations) at the time of the first tsunami arrival. The maximum measured runup using debris marks was  $\sim 3$  m at Boca del Cielo, and maximum inundation distance measured from the shoreline (as shown in Fig. 3f, Table 1) was 190 m in Puerto Arista, corresponding to the coast opposite the epicenter and in the central sector of the Gulf of Tehuantepec (Fig. 2). Runup values tended to decrease toward the southeast, except for PCh, where the first waves were not the highest and the maximum amplitude was reported by tide gauge data as 2.34 m (Fig. 1). In general, our field data agree with the predicted results from the preliminary tsunami model. However, tide gauge signal suggests 2.38 m above mean sea level maximum wave level at 09:50 (GMT), i.e., 5 h later than the arrival of the first tsunami wave, at the PCh station (Fig. 2). The tsunami event and related sea perturbations lasted nearly 48 h.

### 3.3. Tsunami Effects: Erosion/Scour and Deposits

Tsunami scour and erosion were evident near the backshore behind a berm at Punta Arista (Fig. 3f), while tsunami deposits, mainly a sand unit with a sharp basal contact, showing laminations within the sand unit, at the beach face reached up to 32 cm thickness thinning landward up to 172 m inland (Figs. 3b, c, 4c, d, e). We distinguished tsunami deposits from other extreme storm deposits by different means such as tsunami eyewitness reports, still greenish grass and other vegetation that was recently buried by sand transported by the tsunami, buried debris and trash, and sand deposited in houses and fields (Figs. 3, 4). We also revised the NOAA-NHC (2017) database for recent storms near the coast of Chiapas and there is no record of a storm hitting this coast on the previous months of the 8 September tsunami. At Boca del Cielo, minor fractures and minor slumps occurred on the lagoon side of the sand bar, most probably related to the ground shaking

produced by the 8 September 2017 earthquake. A 1.8 m erosional scarp emerged on the beach at Boca del Cielo estuary and across the estuary mouth. It is unclear whether this scarp was formed because of tsunami erosion or a slump. It is also likely that lateral spreading produced this scarp. Figure 4 shows evidence of tsunami flooding, grass buried by tsunami deposits, detached vegetation such as mangrove trees, trees branches broken, debris transported by the tsunami flood and trapped on trees, trash transported by the tsunami and buried by sand, water and debris inundation marks on walls at houses and on trees, swimming pools filled with marine water and sand, and erosional geomorphic features such as pedestals, canals, and fans produced by the tsunami.

### 3.4. Local Societal Response to the Tsunami

We collected information regarding the tsunami early warning system as part of eyewitness interviews during the post-tsunami survey. We asked locals in each town of the surveyed area (8 villages, Fig. 2) about their reaction during and after the earthquake and if they received an official warning of evacuation prior to the tsunami.

The Mexican tsunami early warning system (CAT—Centro de Alerta de Tsunami), created on April 2012, is responsible for issuing tsunami alert bulletins. CAT issued 12 tsunami alert bulletins on 8 September 2017, the first at 04:58:26 GMT (23:58:26 local time), i.e., 9 min and 5 s after the earthquake, and the last at 20:30 GMT (15:30 h local time) (CAT 2017). The first alert was issued 15 min before the first tsunami arrival at Puerto Chiapas. According to official sources, thousands of people were evacuated from the coast (mainly in large towns, e.g., Tapachula). However, the tsunami early warning did not reach people in the small towns along the Chiapas and Oaxaca coasts, except for one town: at Boca de Cielo where a naval station is based, people were alerted and asked to evacuate. This community sits on a sandbar across an estuary; thus a boat was required to enable them to cross to the mainland and higher ground. People on the mainland were self-organized and evacuated, but those without car transport were left behind. Because the Tehuantepec shelf is very shallow (100–300 m) for a very long



distance offshore (> 100 km), tsunami propagation is relatively slow and arrival times from source to coast are often as long as 1 h. Thus, there is more time for

people to respond and evacuate. Two local fishermen from Puerto Arista who were fishing at the beach at the time of the earthquake described it as strong, later

◀Figure 3

Post-tsunami survey observations, Gulf of Tehuantepec, Chiapas. **a** Puerto Arista study area. **b** Evidence of grass covered with sand. **c** Evidence of grass partially covered with sand and vegetation indicating tsunami flow direction (from S to N). **d** Broken mangrove tree branch. **e** Flow depth marked by broken branches and debris on tree. **f** Drone-captured digital elevation model of tsunami effects at site PA2 (location shown in **a**). The tsunami inundation limit (dotted line) is marked by dry, dead vegetation (due to saltwater inundation). Geomorphic features are labeled; letters indicate the location of features shown in detail in **e–g**

saw the sea retreating about 60–70 m, and they ran inland to the nearest hill, but water reached them up to their chest height. Some other eyewitnesses felt the earthquake and described it as strong in Puerto Arista, but they did not evacuate immediately, and some even stayed at the beach. Only when they saw the sea retreating did they evacuate inland on foot or by car. It is likely that the tsunami arrival and maximum wave heights were reached earlier at Boca del Cielo and Punta Arista, where local inhabitants indicated a “short time” elapse after the earthquake for the occurrence of ocean retreat and then the first arrival of the tsunami wave. At El Madresal, a small coastal town in Chiapas, people did not evacuate after they felt the earthquake. Instead, some people walked to the beach to observe the ocean. At San Mateo del

Mar, Oaxaca, an indigenous Ikoot community, local people felt the earthquake and knew of the possibility of a tsunami after a strong earthquake. They whispered in Ikoot language “...Apmaxip nadm ndek...” (“the ocean is going to rise”) (Talle 2017). It is likely that the indigenous Ikoot community had passed through oral tradition their knowledge about tsunamis. On 8 September 2017 at 12:22 h local time, 125 San Mateo del Mar locals were sharing information of the first tsunami warning issued by local cell phone applications. Later at 12:44 h, the Ikoot community was warning local people on Facebook using information from NOAA. The Ikoot community was self-organized, calling people to move to higher ground, and some of them drove to Huazantlán del Río and did not return until the following day. According to the Facebook page (<https://www.facebook.com/SanMateodelmarOaxaca>), damage in San Mateo del Mar occurred during the earthquake but not during the tsunami. Local inhabitants at Colonia Cuauhtemoc, 100 m from the ocean, observed the sea retreating about 50 m and evacuated (Talle 2017).

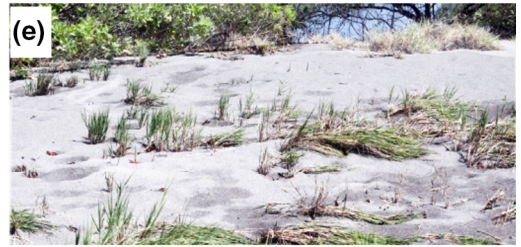
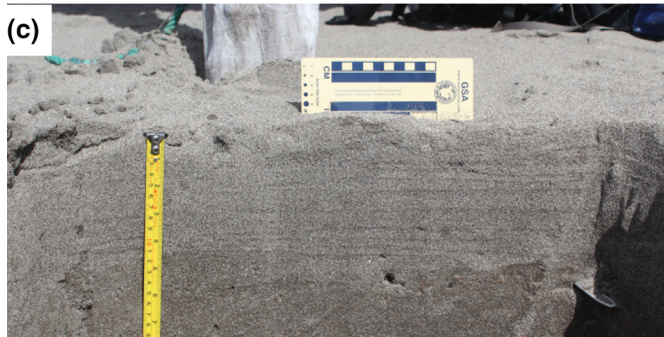
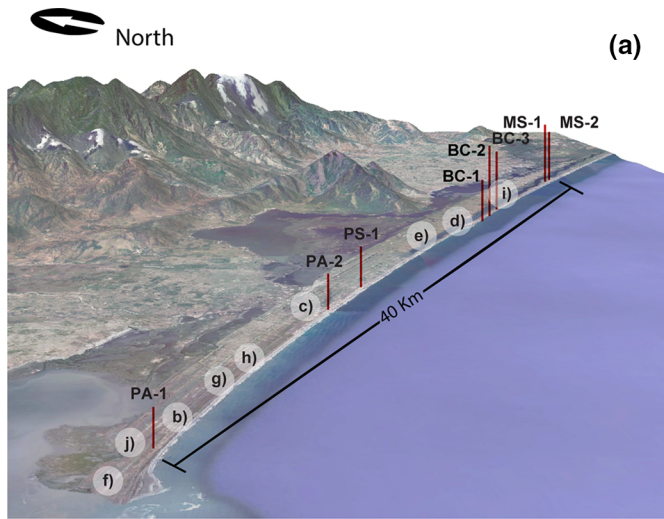
Even though the CAT issued several tsunami warnings, these alerts did not reach most people along the Chiapas coast. The multi-ranked CAT notification system obeys a sequence of notifications:

Table 1

Summary table of physical observations of 8 September 2017 tsunami

Id	Location	Long	Lat	Date	LT	GTM	Z (m)	DFSHL (m)	TLAMT (m)	Notes	Flow depth (m)	Feature measured
1	Madre Sal 2 (MS-2)	– 93.59843	15.796273	9/15/17	10:31:45	15:31:45	1.67	19.21	0.6728	1.00 m Runup		Broken vegetation
2	Puerto Arista 2 (PA-2)	– 93.91003	15.983352	9/14/17	13:01:59	18:01:59	1.87	189.3	0.0525	1.82 m Runup	1.2	Broken vegetation
3	Boca del Cielo 1 (BC-1)	– 93.67091	15.8464	9/14/17	17:39:02	22:39:02	2.3	72.945	– 0.4034	2.70 m Runup		Eyewitness and inundation marks on houses
4	Boca del Cielo 2 (BC-2)	– 93.66848	15.844737	9/14/17	18:16:33	23:16:33	2.3	64.498	– 0.2636	2.56 m Estimated Runup		Broken vegetation
5	Puerto Arista 1 (PA1)	– 93.8069	15.930717	9/14/17	10:46:00	15:46:00	2.16	119.4	0.6949	1.463 m Runup	0.52	Sand and plant debris
6	Boca de Cielo 3 (BC-3)	– 93.67702	15.849475	9/14/17	18:36:00	23:36:00	2.47	55.73	– 0.1762	2.646 m Runup		Debris and inundation marks on poles
7	Madre Sal (MS-1)	– 93.60185	15.798408	9/15/17	10:43:00	15:43:00	1.9	25	0.6856	1.211 m Runup		Debris and inundation marks
8	Playa del Sol 1 (PS1)	– 93.78468	15.918103	9/14/17	13:43:00	18:43:00	2.2	88.4	– 0.1545	2.356 m Runup	0.18	Inundation marks on walls

LT local time, *DFSHL* distance from shoreline, *Z* runup height before correction, *TLAMT* estimated tide level at measurement time (SMN 2017), *Z\_CORR* runup after correction for state of tide at the time of assumed maximum





## ◀Figure 4

Physical observations of the 8 September 2017 tsunami. **a** Chiapas coastal plain and **b–j** the approximate location of the photographs. **b** Evidence of grass covered with sand in the vicinity of point PA-1. **c** Sand deposit on the beach approximately 100 m from the sea at Puerto Arista town (please see text for description of tsunami deposit). **d** Sand deposit located on the beach, near point PS-1 (please see text for description of tsunami deposit). **e** Sand deposit covering grass in the vicinity of PA-1. **f** Pedestals, evidence of erosion in sand dunes next to an estuary. **g** Pedestals, at the interface of the beach and the beach ridges, also exposed roots of mangroves detached from the ground. **h** Area with evidence of tsunami inundation showing a protruding trunk and detached vegetation by the tsunami. **i** Overview of the beach between points BC-2 and BC-3 shows traces of vegetation debris transported by the tsunami beyond the high tide mark (latest not shown in picture). **j** < 1-m-high grasses that were bent in the direction of the tsunami flows in the vicinity of PA-2

(1) the CAT to the Federal government; (2) then to the Federal civil protection office; (3) then to the state-level civil protection office; (4) then to the local municipality civil protection office; and (5) then the notifications are shared with the people. We do not know where in this chain system was the failure to notify the people of small villages on the coast of Chiapas and Oaxaca.

#### 4. Discussion and Conclusions

The rapid response post-tsunami survey after the 8 September 2017 earthquake resulted in the recovery of important data on the characteristics and distribution of the associated tsunami impact along the Chiapas coast, and of the societal response. We noted maximum tsunami runup of  $\sim 3$  m at Boca del Cielo, although we are unsure of the exact arrival time. The first tsunami arrival time recorded by tide gauges indicate 05:14 (GMT) at Salina Cruz and 05:27 (GMT) at Puerto Chiapas, i.e., between 25 and 38 min after the earthquake. Tide gauge data indicate that the tsunami occurred at low tide. The maximum heights recorded occurred 5 h later.

The 8 September 2017 tsunami was triggered by a 58 km depth earthquake on a steep, northeastward-dipping normal fault, near the slab bending of the subducting oceanic Cocos Plate, and not at the Tehuantepec seismic gap along the megathrust, where a significant earthquake was expected. Because tsunami modeling and early warning

methods are associated mainly with subduction earthquakes, the Chiapas case offers an opportunity to develop these methods for other types of tsunamigenic earthquakes. The megathrust may possibly still have enough stress to rupture along the Tehuantepec seismic gap. This calls for studies on historical and geological evidence of past megathrust earthquakes and tsunami events or to determine whether other faults ruptured along this sector of the Mexican subduction zone. The tsunami struck the Chiapas coast prior to the arrival of official warnings to the residents of small coastal towns. Thus, a tsunami early warning system with a direct warning to all coastal communities is needed. Even though the residents of some indigenous communities and coastal settlements evacuated under their own initiative, some residents did not evacuate. Tsunami educational material has been produced in different languages and made available online (e.g., leaflet by Ortiz and Ortiz 2014); however, its distribution has not been effective. This emphasizes the importance of community-based education and awareness programs that reach people of all coastal communities (NRC 2017).

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